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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 492

INFLUENCE OF FUSELAGE ON PROPELLER DESIGN

By Theodor Troller

From Zeitschrift für Flugtechnik und Motorluftschiffahrt  
July 28, 1928

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Washington  
December, 1928



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INFLUENCE OF FUSELAGE ON PROPELLER DESIGN.\*

By Theodor Troller.

The works of Bienen, Von Karman and Helmboldt have given a simple and sufficiently accurate method for designing detached propellers.\*\* Previous proposals for the design of propellers for actual working conditions and the method for the determination of the best possible efficiency of propulsion of an assemblage of screw-propelled bodies were not so thoroughly worked out. The best treatise on this subject is probably the one by Helmboldt.\*\*\*

In the present paper I shall not consider the problem of the best arrangement of airplane and propeller, but only a simple method for designing a propeller for a given arrangement of the airplane parts. The inflow to the propeller and hence the efficiency of the propeller is affected most by the fuselage.

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\*"Zur Berücksichtigung des Rumpfes beim Luftschraubenentwurf," a communication from the Aerodynamic Institute of the Aachen Technical High School, Zeitschrift für Flugtechnik und Motorluftschiffahrt, July 28, 1928.

\*\*Bienen and Von Karman, V.D.I. (Zeitschrift des Vereines deutscher Ingenieure), 1924; Helmboldt, "Zur Aerodynamik der Treibschraube," Zeitschrift für Flugtechnik und Motorluftschiffahrt, 1924.

\*\*\*Helmboldt, "Nachstromschrauben," Werft, Reederei, Hafen, 1927, and "Ueber den Vortriebswirkungsgrad," Werft, Reederei, Hafen, April, 1928. See also A. Betz, "Considerations on Propeller Efficiency" (N.A.C.A. Technical Memorandum No. 481, 1928), and "Propeller Problems" (N.A.C.A. Technical Memorandum No. 491, 1928).

The effect of the wings and of the other parts lying in the propeller slip stream is much less and is also more difficult to determine.

In order to determine the influence of the fuselage on the propeller design, we must first ascertain the flow conditions in the plane of the propeller, which are affected by the shape of the fuselage. Instead of the troublesome experimental investigation of the flow about the fuselage, a mathematical method can be used with good approximation. The fuselage is approximately represented by a body of revolution and the latter in turn by a system of sources and sinks corresponding to the method employed by Von Karman for calculating the pressure distribution on the hull of an airship.\* The sources and sinks are shown in constant strength over a stretch  $a$  along the axis.

It follows that the stream function of the resultant flow is

$$\psi = \frac{U r^2}{2} - \sum_{i=1}^n \frac{Q_i}{4\pi} \left( 1 + \frac{\rho_{i'} - \rho_{i''}}{a} \right),$$

in which

$U$  = air speed in horizontal flight,

$Q_i$  = strength of source in section  $i$ ,

$\rho_{ik'}$ ,  $\rho_{ik''}$  = distance of reference point from front  
or rear end of a source stretch,

$r_k$  = distance of reference point from axis,

$a$  = length of source stretch.

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\*Von Karman, "Berechnung der Druckverteilung an Luftschiffkörpern," Abh. a.d. Aerodyn. Inst. d. T. H. Aachen, No. 6.

The source strengths are calculated from the streamline  $\psi = 0$ , which must yield the axis and the surface curve of the fuselage. For determining the  $n$  source strengths the equation of the streamline  $\psi = 0$ , yields  $n$  equations by taking  $n$  points of the surface curve for reference points. If we put

$$\frac{Q_i}{2 U \pi a^2} = z_i \quad \text{and} \quad 1 + \frac{\rho_{ik}' - \rho_{ik}''}{a} = c_{ik},$$

we thus obtain

$$\begin{array}{ccccccc} c_{11} z_1 + c_{21} z_2 + \dots c_{n1} z_n & = & \left(\frac{r_1}{a}\right)^2, \\ \vdots & & \vdots \\ c_{1n} z_1 + c_{2n} z_2 + \dots c_{nn} z_n & = & \left(\frac{r_n}{a}\right)^2. \end{array}$$

Since we are here interested only in the flow in the plane of the propeller, i.e., at the nose of the fuselage, it is only necessary to replace the bow by the system of sources and sinks. A small number (3-5) of constant source stretches will furnish a close enough approximation for our present purpose. Since, however, a systematic solution of the system of equations with sufficient mathematical accuracy would require too extensive calculations, it is preferable to solve the equations by estimating the roots and by verifications. After the values  $z_i$ , and hence the source strengths, are thus found, the velocities in the plane of the propeller become

$$u_x = U - U \frac{a}{2} \sum_{i=1}^n \left( \frac{1}{\rho_{ik}''} - \frac{1}{\rho_{ik}'} \right) z_i,$$

$$u_r = U \frac{a}{2r} \sum_{i=1}^n \left( \frac{x_i''}{\rho_i''} - \frac{x_i'}{\rho_i'} \right)$$

in which

$u_x$  = axial velocity component,

$u_r$  = radial " "

$x_i'$  ,  $x_i''$  = distance of front or rear end of source stretch from the propeller plane.

Herewith the necessary values for the design are obtained.

We must first determine the best thrust distribution before undertaking the constructive calculation of the propeller. This is determined on the principle that the efficiency must be made as great as possible, i.e., that the losses in the energy transformation must be as small as possible. We here disregard the friction losses, which are of slight importance from this viewpoint. We must then regard the kinetic energy in the slip stream as small. In considering the energy in the slip stream far behind the fuselage, we disregard the contraction due to the action of the propeller and the disturbances in the flow caused by the tail group, etc. Let  $w_x'$   $\omega_r'$   $r_x$  represent the velocities and radii in the propeller plane;  $w'^{red}$   $\omega'^{red}$   $r^{red}$ , the corresponding values (located on the same streamline) in the flow behind the fuselage. As in the case of the detached propeller, we then have the condition

$$\int_0^{R_{red}} \left( U + \frac{w'_{red}}{2} \right) \left( \frac{w'^2_{red}}{2} + \frac{r^2_{red} \omega'^2_{red}}{2} \right) r_{red} dr_{red} = \text{Min.},$$

whereby

$$2\pi \gamma \int_0^{R_{red}} \left( U + \frac{w'_{red}}{2} \right) w'_{red} r_{red} dr_{red}$$

is given.  $w'_{red}$  is the axial velocity to be added and  $r'_{red}$ ,  $\omega'_{red}$  is the resulting peripheral velocity on the radius  $r$  in the slip stream. We can best determine  $R_{red}$  from the condition that

$$2\pi \int_0^R u_x r_x dr_x = U R^2_{red} \pi$$

in which

$R$  = propeller radius;

$U$  = air speed

and

$u_x$  = axial velocity in the propeller plane.

We then have

$$R_{red} = \sqrt{2 \int_0^{R_{red}} \frac{u_x}{U} r_x dr_x}.$$

The integral is easy to determine graphically. Again it follows from the minimum condition that

$$\eta_i = \frac{U dS}{U dS + \frac{dQ}{2} \frac{w'^2_{red}}{2} + \frac{dQ}{2} \frac{r'^2_{red} \omega'^2_{red}}{2}}$$

is to be kept constant along the radius,  $dS$  being a thrust element and  $dQ$  being the mass of air flowing through a circular element per unit of time. On further introducing  $dS = dQ w'$ , we obtain

$$\eta_i = \frac{1}{1 + \frac{w'_{red}}{2U} + \frac{r_{red}^2 \omega'^2_{red}}{2U w'_{red}}} = \text{const.},$$

or, finally, as the condition for the best thrust distribution,

$$w'_{red} + \frac{r_{red}^2 \omega'^2_{red}}{w'_{red}} = c U \quad [c = \text{const.}]$$

with the subordinate condition

$$2\pi \frac{\gamma}{g_0} \int_0^{R_{red}} \left( U + \frac{w'_{red}}{2} \right) w'_{red} r_{red} dr_{red} = S.$$

The simple relation

$$r_{red} \omega'_{red} = w'_{red} \lambda'_{red},$$

which exists for the detached propeller, no longer obtains here, but we have the following relations in which  $\lambda$  = effective pitch angle and  $\lambda'$  = "induced" pitch angle.

$$r_x \omega_x' = w_x' \lambda_x' = w_x' \lambda_x \frac{1}{\eta_i} \quad (\text{analogous to detached propeller}),$$

$$w_x' = w'_{red} \frac{u_x}{U},$$

$$\lambda_x = \frac{u_x}{r_x \omega} = \frac{U}{r_{red} \omega} \frac{u_x}{U} \frac{r_{red}}{r_x},$$

$$(r_{red} \omega'_{red}) = (r_x \omega_x') \frac{r_x}{r_{red}} \quad (\text{from the constancy of the spiral}).$$

It then follows that

$$r_{red} \omega'_{red} = w'_{red} \left( \frac{u_x}{U} \right)^2 \lambda_{red} \frac{1}{\eta_i} = w'_{red} x,$$

$x$  being variable along the radius and dependent on the shape

of the fuselage and on the pitch angle of the propeller. The condition for the best thrust distribution now reads

$$w'_{red} (1 + x^2) = c U.$$

The constant  $c$  is found from the equation for the total thrust

$$S = 2\pi \frac{\gamma}{g} \int_0^{R_{red}} \left( U + \frac{c}{2(1+x)} \right) \frac{c-U}{1+x^2} r_{red} dr_{red}.$$

The values of  $w'$  can be calculated for any value of  $c$ , but most conveniently for  $c = 1$ . ( $\eta_i$  is estimated at first. A small error in estimating does not appreciably affect the subsequent calculation.) We determine graphically the integrals

$$2\pi \frac{\gamma}{g} U^2 \int_0^{R_{red}} \left( \frac{1}{1+x^2} \right) r_{red} dr_{red} = a$$

and

$$\pi \frac{\gamma}{g} U^2 \int_0^{R_{red}} \left( \frac{1}{1+x^2} \right)^2 r_{red} dr_{red} = b.$$

We then have

$$a c + b c^2 = S, \dots$$

whence

$$c = -\frac{a}{2b} \left( + \sqrt{\frac{a^2}{4b^2} + \frac{S}{b}} \right)$$

We now have all the requisite data for the determination of the thrust distribution and also the induced efficiency of the propeller

$$\eta_i = \frac{1}{1 + \frac{c}{2}}$$

The allowance for the finite number of blades can now be made in the same way as for the detached propeller. The propeller thrust  $S_\infty$ , which would be attained with an infinite number of blades, is made the basis of the calculation. It depends on the desired thrust according to the well-known formula

$$S_\infty = S \left( \frac{1}{1 - 1.39 \frac{\sin \beta}{z}} \right)^2,$$

( $\beta$  is here given by the pitch angle of the blade tips, and  $z$  is the number of blades. See Bienen and Von Karman.)

With this value  $S_\infty$  we must now determine  $c$ . Then the values of the thrust elements  $dS$  and also  $w'$  must be multiplied by the  $k$  values, which are likewise given in the article by Bienen and Von Karman. The further constructional computation is made in just the same way as for detached propellers. From

$$\begin{aligned} dS &= dA \cos \beta' - dW \sin \beta' \\ &= c_a z t d z_x (u_x^2 + r_x^2 \omega^2) \\ &\quad \frac{\gamma}{2g} (1 - \epsilon \lambda_{x'}) \cos \beta_{x'} \end{aligned}$$

( $dA$  = lift and  $dW$  = drag of the blade element) and

$$dS = \frac{\gamma}{2g} \left( U + \frac{w'_{red}}{2} \right) w'_{red} 2 r_{red} \pi d r_{red} K$$

we obtain

$$c_a zt = \frac{2 r_{red} \pi d r_{red} \left( U + \frac{w'_{red}}{2} \right) w'_{red}}{d r_x r_x^2 \omega^2 (\lambda_x^2 + 1) (1 - \epsilon \lambda'_x) \cos \beta'_x} K$$

$$= K \frac{2 \pi U^2}{r_x \omega^2 (\lambda_x^2 + 1) (1 - \epsilon \lambda'_x) \cos \beta'_x} \left[ \frac{c}{1 + x^2} + \frac{1}{2} \left( \frac{c}{1 + x^2} \right)^2 \right]$$

(z = number of blades,

t = chord of blade section or profile,

$c_a$  = lift coefficient,

$\epsilon$  = drag-lift ratio of profile for infinite span,

$\lambda'_x = \lambda_x \eta_i$ ,

$\beta$  = arc tan  $\lambda$ .)

The correct pitches can also be given the blade sections from the previously found inflow velocities. Any consideration of the radial velocities, which necessitate a lengthening of the effective blade chord and a reduction in the angle of attack, is not generally necessary. The whole process requires but little more time than the construction of detached propellers in the usual manner.

An example will illustrate the application of the method. Let us suppose that a propeller is to be designed for an airplane having a fuselage with a maximum diameter of 1 m (Fig. 3). The R.P.M. of the engine shaft is  $n = 1200$ . The air speed for normal horizontal flight is estimated in advance to be

$v = 24$  m/s. The desired thrust  $S = 40$  kg. The maximum allowable propeller diameter  $D = 2$  m. First the nose of the fuselage is replaced by sources. Four source stretches are then adopted. Figure 4 shows their location, as also the location of the chosen reference points. The following table contains the values  $c_{in}$ , which are determined from the values  $\rho_{ik}'$ ,  $\rho_{ik}''$  taken from Figure 3.

	1	2	3	4
I	1.0	1.225	1.425	1.55
II	0.65	1.0	1.2	1.375
III	0.475	0.75	1.0	1.2
IV	0.275	0.575	0.775	1.0

The values  $c_{ik}$  and  $r_k$  (likewise taken from Figure 3) give the equations

$$1.0 \quad z_1 + 0.65 \quad z_2 + 0.475 \quad z_3 + 0.275 \quad z_4 = 8.6,$$

$$1.225 \quad z_1 + 1.0 \quad z_2 + 0.75 \quad z_3 + 0.575 \quad z_4 = 16.0$$

$$1.425 \quad z_1 + 1.2 \quad z_2 + 1.0 \quad z_3 + 0.775 \quad z_4 = 20.6,$$

$$1.55 \quad z_1 + 1.375 \quad z_2 + 1.2 \quad z_3 + 1.0 \quad z_4 = 23.0.$$

By estimating and verifying we obtain, as an approximate solution, the values

$$z_1 = 0, \quad z_2 = 4, \quad z_3 = 20, \quad z_4 = -8.$$

from which we calculate the velocity distribution as shown in

Figure 5, and further, from the continuity condition, the corresponding radii  $r_{red}$  and  $r_x$ . The value of  $\eta_i$ , which is required for the determination of  $x$ , we estimate as follows.

For the detached propeller, according to Bienen and Von Karman, we have

$$\eta_i = \frac{2}{1 + \sqrt{1 + \sigma}} \left( 1 - \frac{\sigma \lambda^2}{2} \right)$$

in which  $\sigma$  represents the load intensity of a propeller with an infinite number of blades. Here we obtain  $\eta_i = 0.89$ . By using the load intensity corresponding to the "reduced propeller slip stream" for the determination of  $\eta_i$ , we get  $\eta_i = 0.88$ .

The correct value of  $\eta_i$  lies between these two. The above-described calculation gives  $c = 0.226$  and  $\eta_i = 0.884$ . The accurate determination of  $\eta_i$  in this case is really superfluous. It would be sufficient to calculate  $x$  and  $c$  from the estimated value. Figure 5 shows the thrust distribution according to the above-described calculation method and also for the corresponding detached propeller.

Translation by Dwight M. Miner,  
National Advisory Committee  
for Aeronautics.

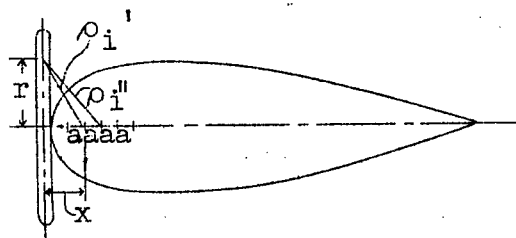


Fig. 1

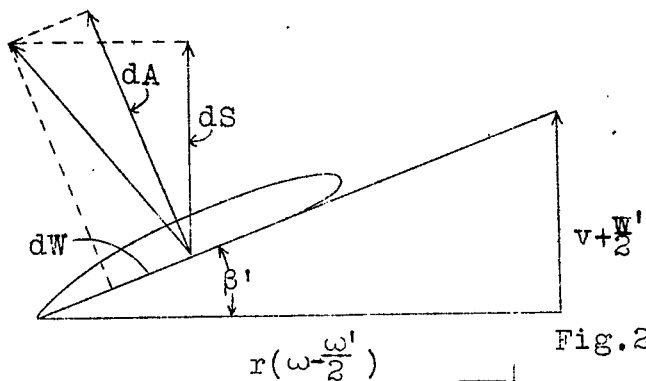


Fig. 2

Fuselage dimensions.

$\frac{x}{l}$	$d$
0.1	0.99
0.2	1.00
0.4	0.95
0.6	0.75
0.8	0.45

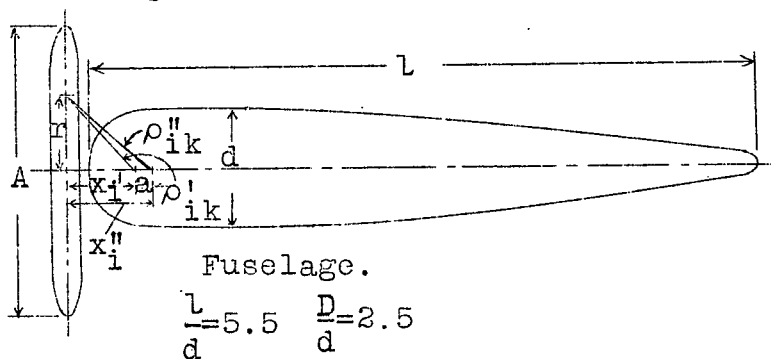


Fig. 3

Fuselage.  
 $\frac{l}{d} = 5.5$   $\frac{D}{d} = 2.5$

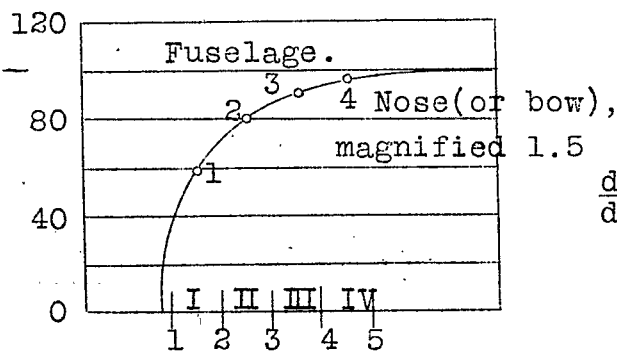


Fig. 4

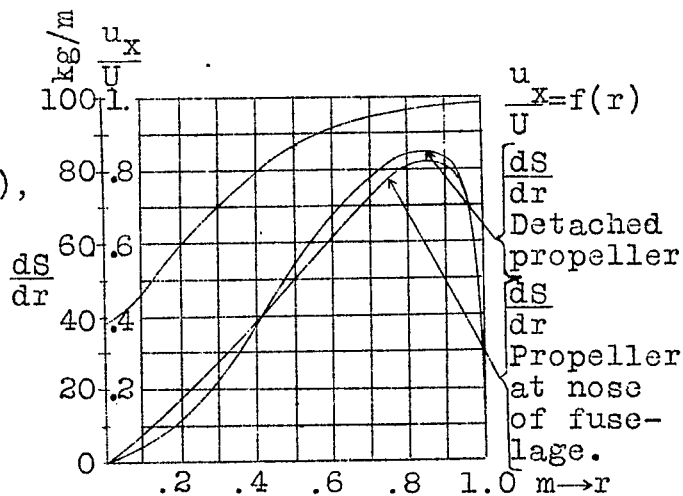


Fig. 5

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